Applied CO_2 Mineralization Opportunities and Challenges

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Lawrence, KS

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Photo: Andrea Starr (PNNL

Health, Safety, and Environment Share: Everyday Respect

- Leaders need to be the shining examples of everyday respect
- Caring, courageous and curious leadership
- Elevate process over results
- Cultivating talent, not teams

5 Ways To Promote Respect In The Workplace

- Choose Your Words Carefully
- Make Soft Skills a Priority
- Resist All Forms of Exclusion
- Clearly Articulate Zero Tolerance for Harassment
- Get Transparent

Basalts Offer Accelerated Risk Reduction For Carbon Storage

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MINERALIZATION SETTINGS

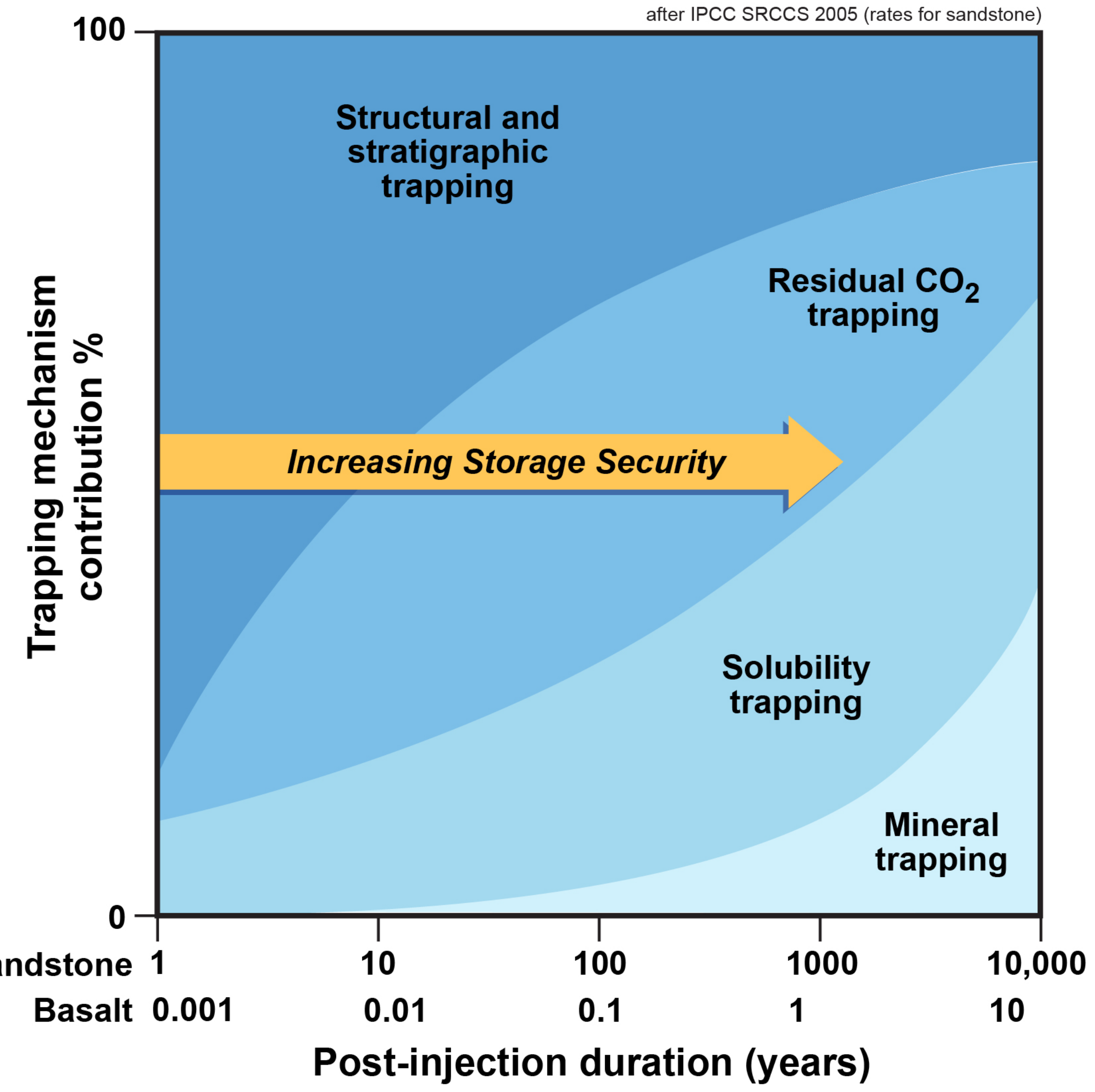
- Targets for in situ CO_2 mineralization include:
  - Porous reservoirs (e.g., basalts)
  - Fractured reservoirs (e.g., peridotite, serpentinite)
  - Hybrid systems (e.g., fractured basalt-hosted geothermal reservoirs, basalt-rich sandstones)
- Ex situ mineralization efforts focus on mine tailings, soil amendments, and engineered systems that leverage non-ambient conditions found at depth

BASALT GEOCHEMISTRY

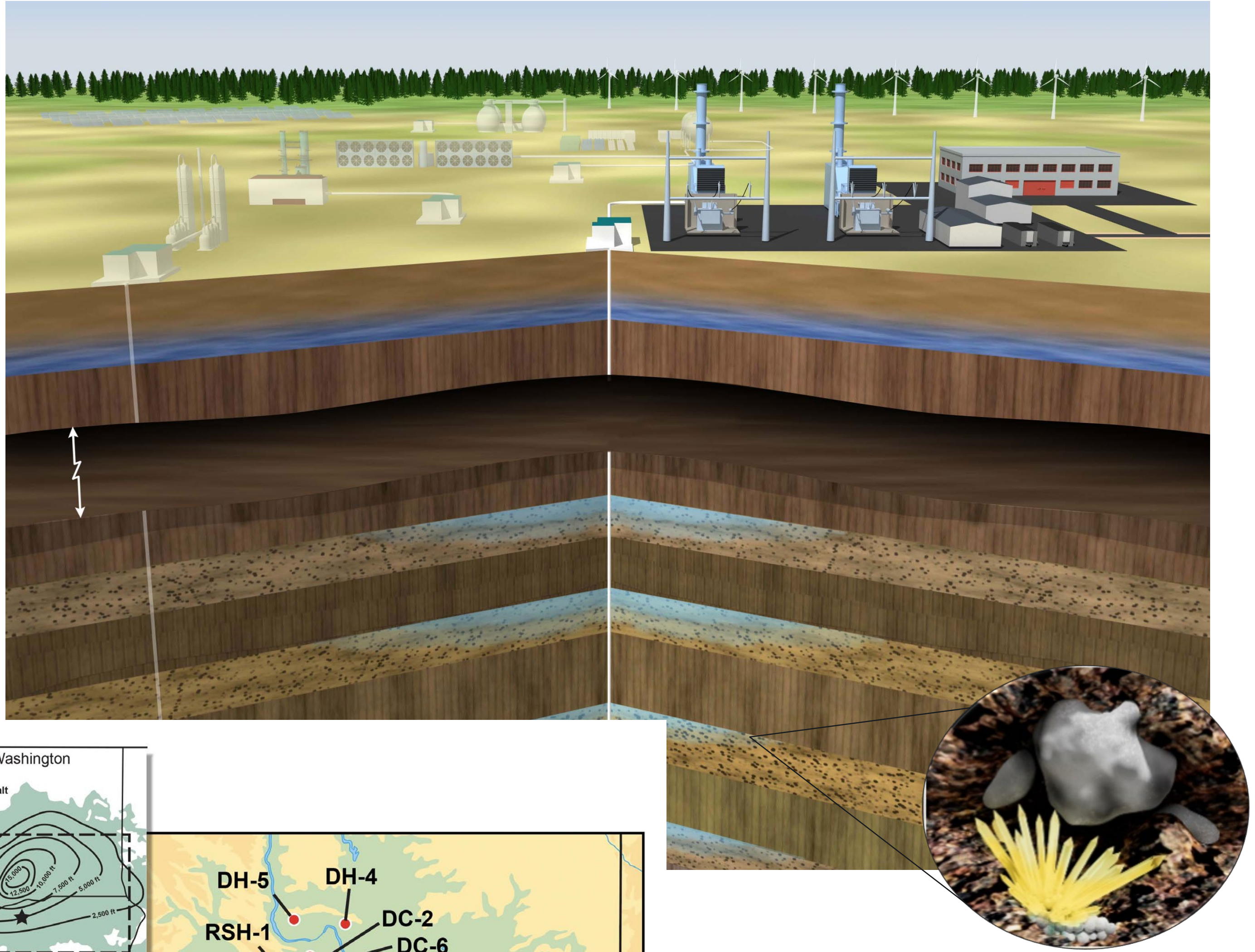
- Basalts are comprised of crystalline minerals (feldspars, pyroxenes, olivine) within a highly reactive glassy matrix
  - carbonate-forming cations (e.g., Ca^{+2}, Fe^{+2}, Mg^{+2}, and Mn^{+2})
- Carbonate type controlled by depth, temperature, surface area, pre-existing secondary minerals, pressure, & water chemistry

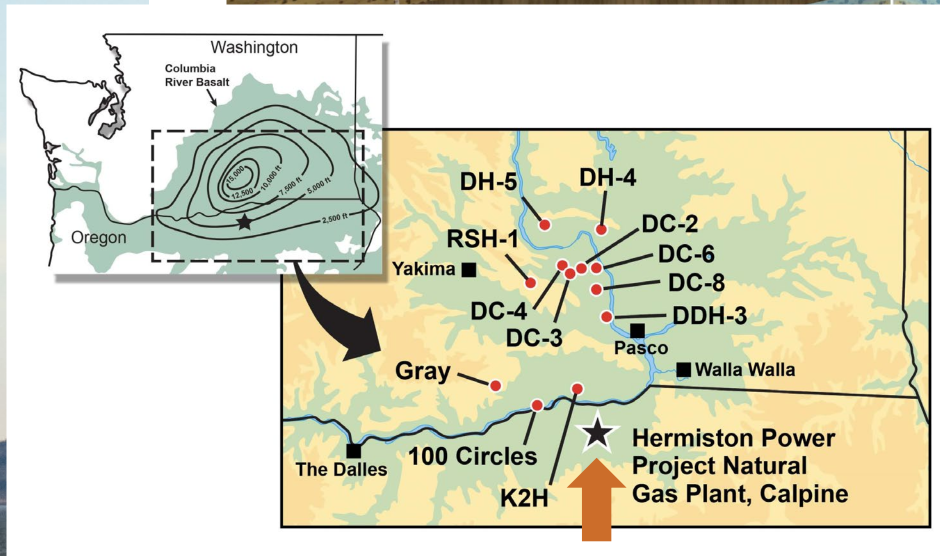
Basalts convert CO_2 to solid minerals much more rapidly than other rock types. Mineralized CO_2 is immobile and poses no risk of leakage. Current research needs to focus on key questions and knowledge gaps that limit global commercial deployment.

Evolution of CO_2 trapping mechanisms in sandstone and basalt reservoirs



CarbonSAFE HERO Phase II Provides an Opportunity to Gain Insights into Deep Layered Basalts for CO_2 Storage





HERO (University of Wyoming and PNNL) represents the first ever basalt-hosted CO_2 storage hub in the nation and the first commercial CO_2 storage development project in the Pacific Northwest.

Scope includes:

- Drill stratigraphic test well at the Hermiston Power Project (Hermiston, Oregon)
- Engage community, industry, governmental and regulatory stakeholders early and often
- Full characterization suite including wireline logging and core testing
- Incorporate stratigraphic data into regional geologic model
- **Complete reservoir simulation to provide uncertainty-bounded estimates of regional capacity, injection rates and mineralization rates**
- Evaluate storage complex sustainability for commercial injection volumes and timescales
- Identify priority areas and options for acquisition of new datasets to resolve key uncertainties advancing to Phase III

Opportunities:

- Regulatory and community stakeholder engagement
- Establishing a repository (Reactive Rock Database) and access to samples, and reservoir data (all informal at the moment)
- Developing new laboratory testing methodologies to assess mineral carbonation

Derisking via Demonstration: Leveraging Field Sites to Prove Out Reservoir Simulators

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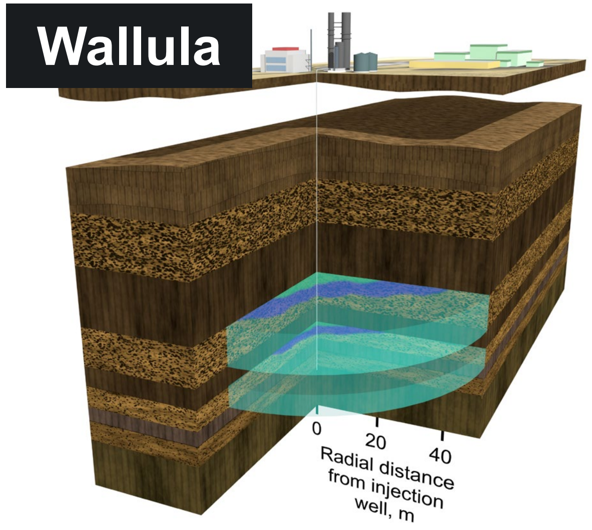
- ✓ Reservoir simulations: history matching and forecasting from demonstration sites
  - Data representing before, during, and after injection
  - Simulations for ground-truthing CO_2 mineralization
- ✓ Reactive transport code comparison
  - Utilization of demonstration sites to establish a set of problems
  - Create complex problems for realistic conditions
  - All codes would see improvement
  - This has been successfully done (e.g. NETL gas hydrates and GTO geothermal reservoirs)
- ✓ Sample repository from demonstration projects
  - Wallula informally shared with eight institutions
  - Establish a protocol for securing and sharing samples
- ✓ Geomechanical assessment; adapting geophysical tools for basalt characterization and monitoring

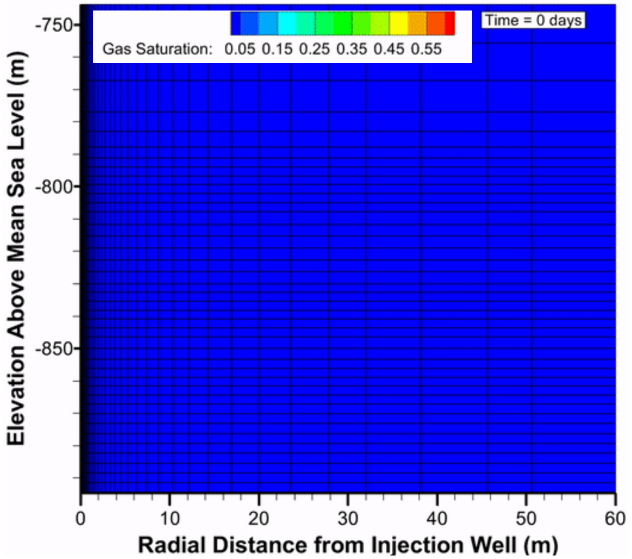
Opportunities to Solve Challenges:

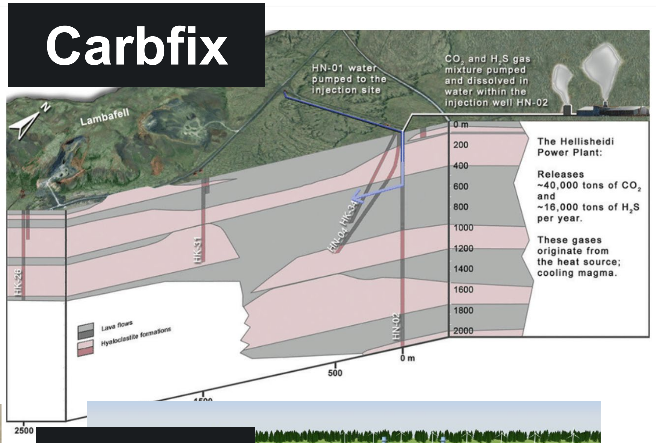
- We have existing field sites (and future field sites) that can be used for code comparison. **The outcome:** Improvements to all participating codes and support EPA in the permitting process.

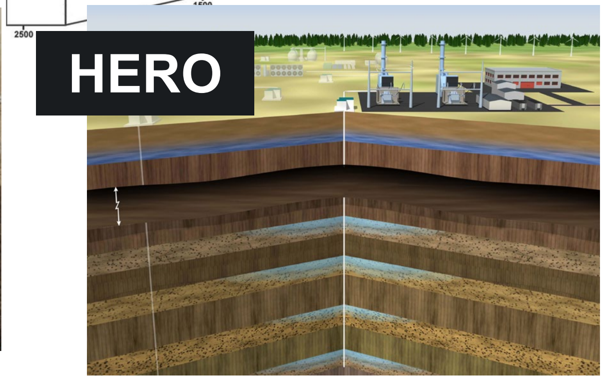
Reactive Rock Sample Share

- Harvard
- UMN
- INL
- Yale
- WUSTL
- Sandia
- UWyo
- Columbia









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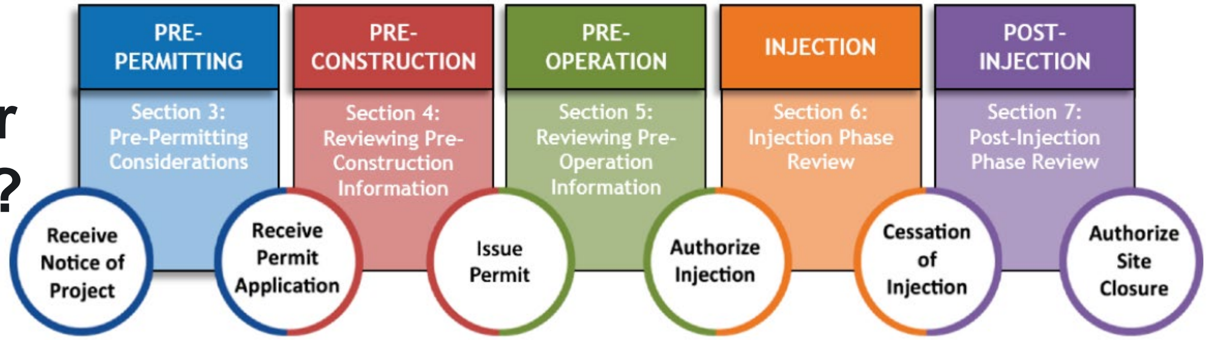
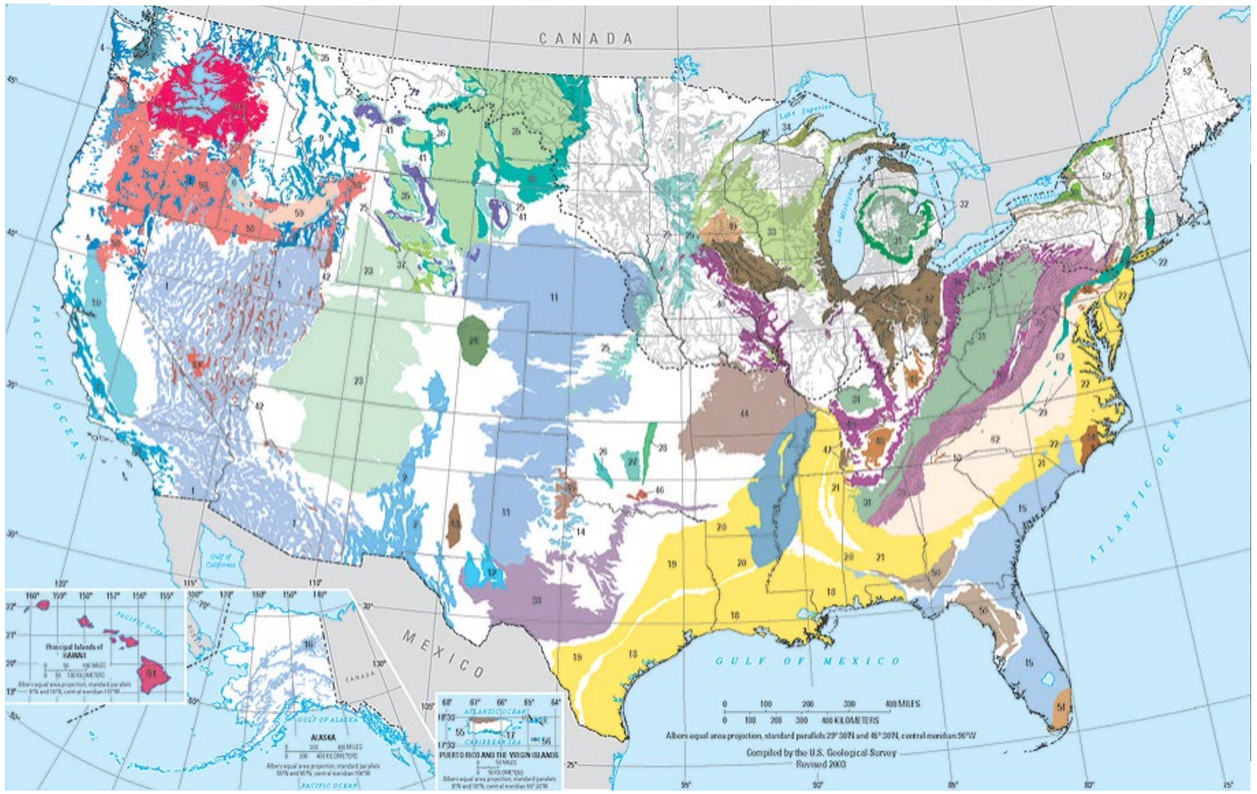
Challenges for Class VI permitting Include Data Scarcity, Limited Field Demonstration Sites, and Experience



Current regulation framework is designed specifically for deep saline, but can it accommodate CO_2 mineralization?

- ✓ What does EPA need to make a determination?
- ✓ Do we need new characterization methods?
  - Pressure monitoring and geochemical sampling as primary monitoring mechanisms
  - What emerging technologies can we leverage?
- ✓ Should seismic be the gold standard?
  - Seismic as secondary or tertiary validation tool
  - Accessing existing seismic is difficult and expensive
- ✓ Attribution of pressure reductions to mineralization vs migration
- ✓ Guidance on water quality resources
  - USDW 10,000 (mg/L) TDS limit
  - Will exemptions be considered? If so, how?
  - Brine extraction/treat/reuse for pressure management



Principal aquifers of the United States (USGS)

Opportunities:

- Partner with US EPA, USGS, state surveys, et al. to address basalt-specific data needs for Class VI permitting
- Collaboration with host communities and stakeholders to understand benefits and impacts (e.g., groundwater resources).
- Leverage field demonstration sites more broadly throughout the research community by applied and fundamental science teams
- **Industry seeks regulatory and technical support for Class VI permits that account for risk reductions**

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Stakeholder and Community Outreach is Strategic for Clean Energy Project Acceptance

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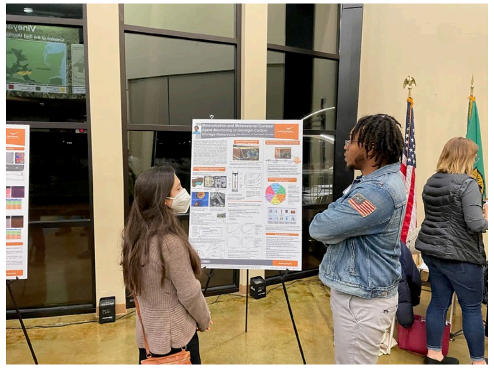
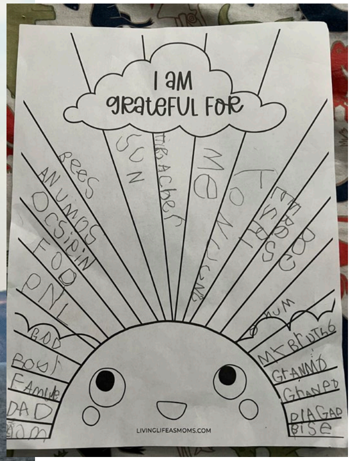
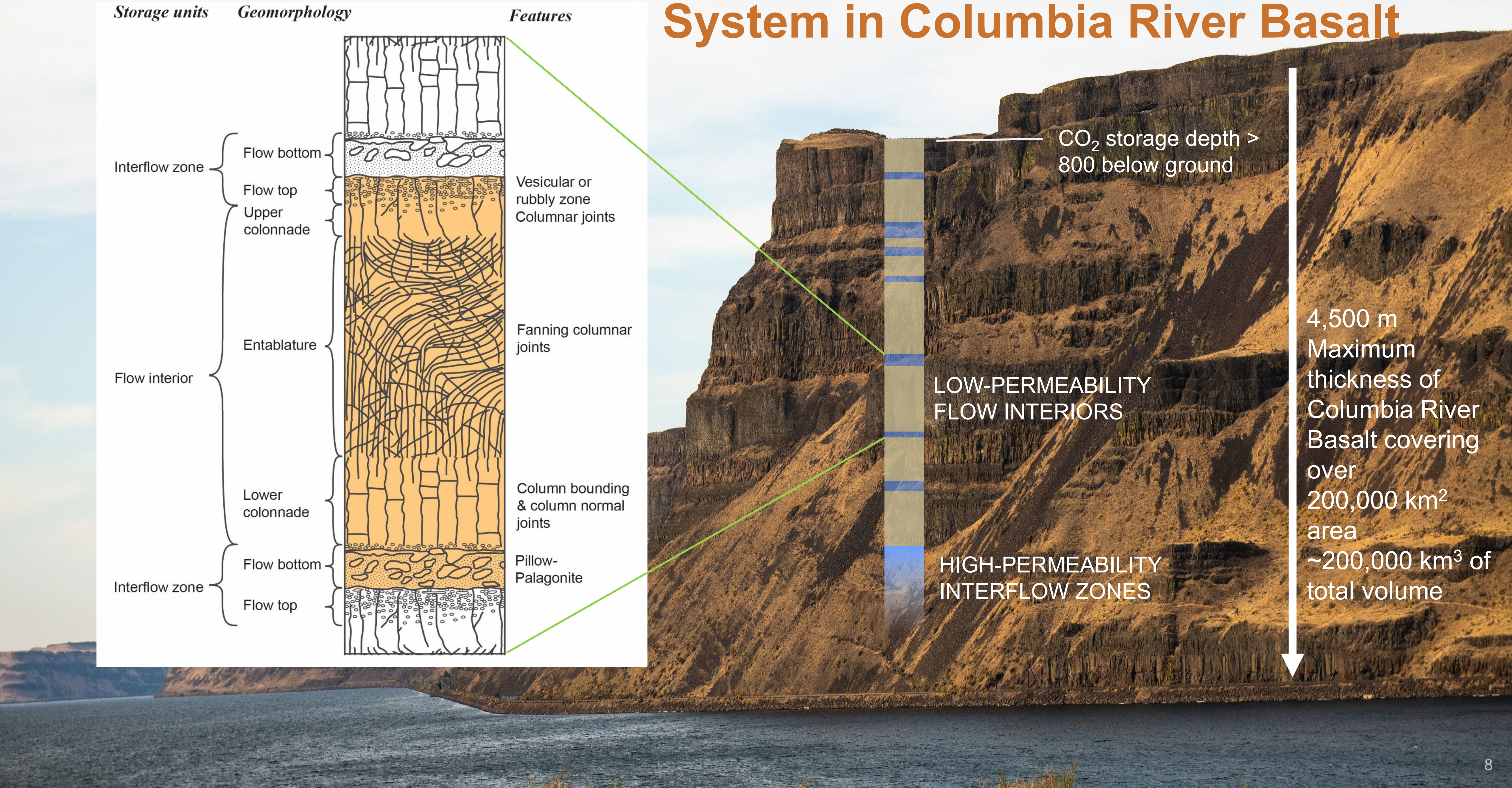
- Demonstration of benefits to communities that are hosting these clean energy projects
- Early engagement is critical to gain acceptance
- Next generation scientist from local communities



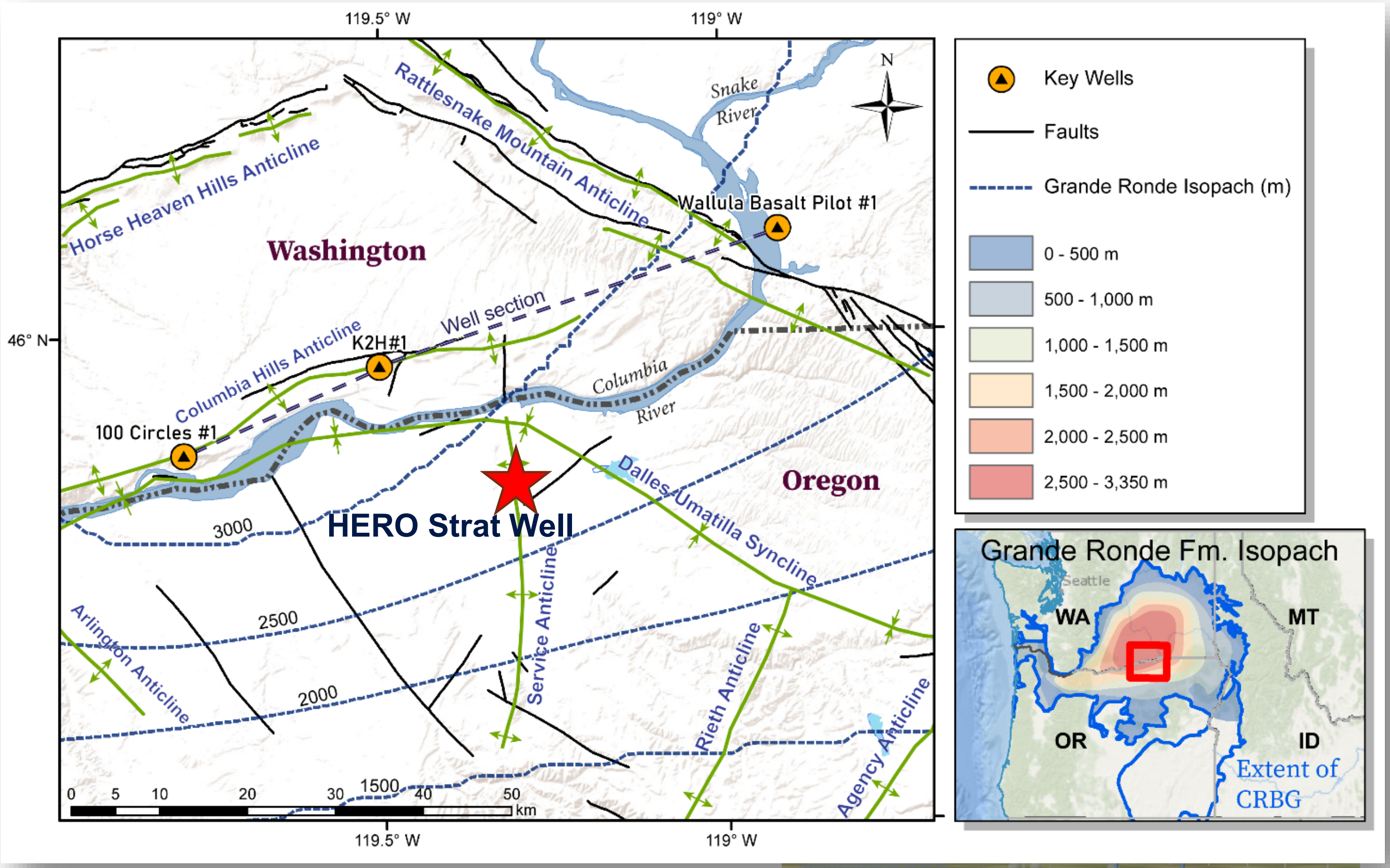


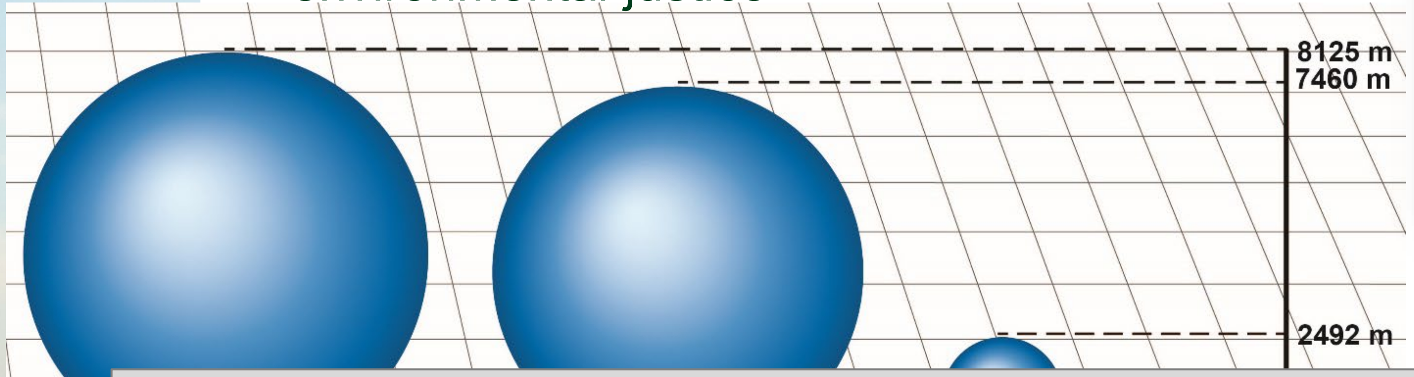
Thick, Extensive, Stacked Storage System in Columbia River Basalt



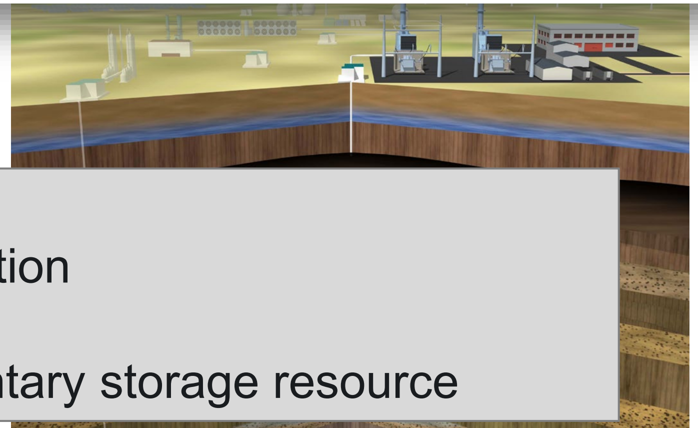
Challenge for HERO CarbonSAFE ($11 M) to extend learnings and accelerate deployment of commercial CO_2 storage projects in basalt

- 1st regional-scale carbon storage resource estimation in the CRBG
- Pasco Basin area (~10,000 km^2) offers up to 352 billion (P10) tons of storage resource in basalt
- HERO will assess feasibility of commercial-scale GCS in the Columbia River Basalt
- Leveraging expertise from Basalt Waste Isolation Project, Wallula, and Carbfix' Orca project to prepare the project for future commercialization efforts
- Developing plans for engagement, DEIA, and environmental justice





Cao et al, 2023. Gigaton Commercial-Scale Carbon Storage and Mineralization Potential in Stacked Columbia River Basalt Reservoirs

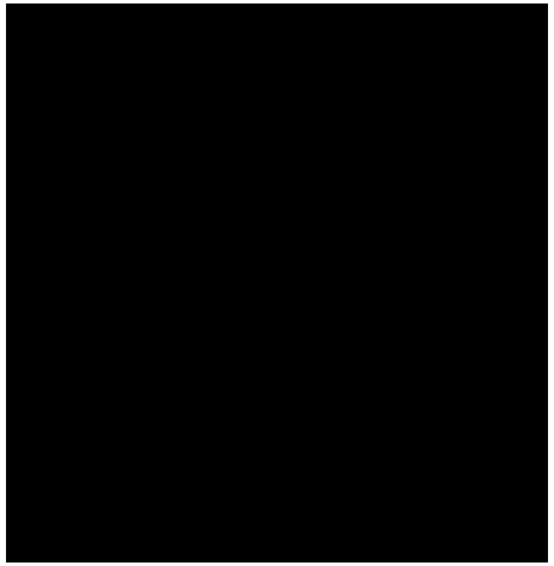


Opportunities:

- Establishing data-driven mineralization storage estimation methods through reactive transport simulation
- Ready the Pacific Northwest region for commercial-scale CO_2 injection projects
- Offer alternative geologic carbon storage options for areas without easy access to traditional sedimentary storage resource

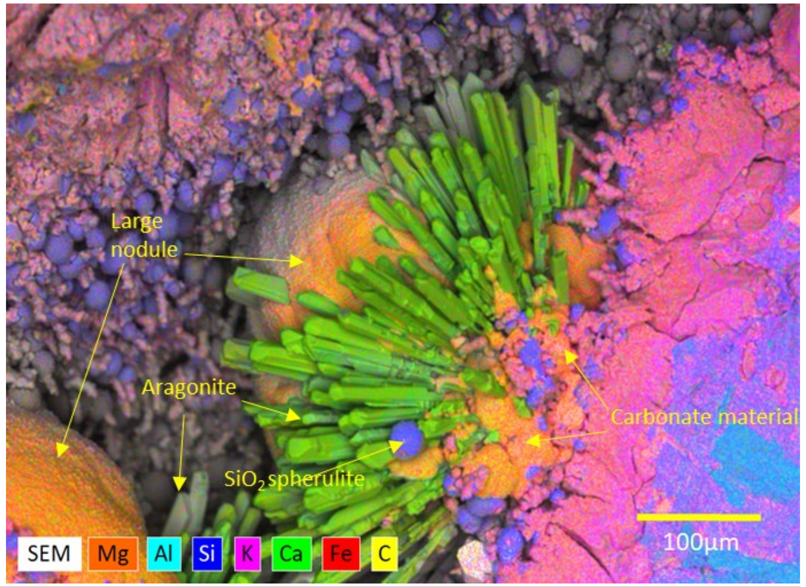
Unparalleled understanding of reaction pathways benchmark Reactive Transport modeling

Pore network architecture



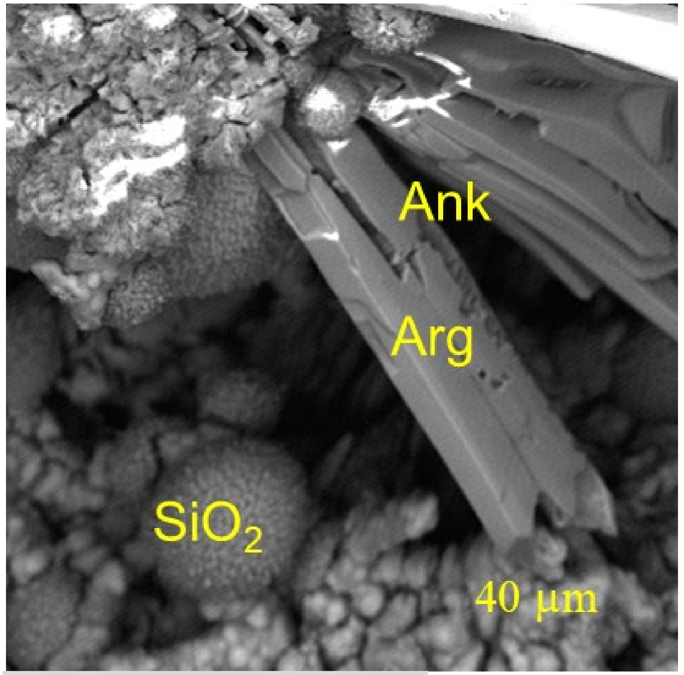
Battu et al. 2022, *in prep*

SEM image and EDS map of aragonite and carbonate nodules in a pore (870.2 m bgl)



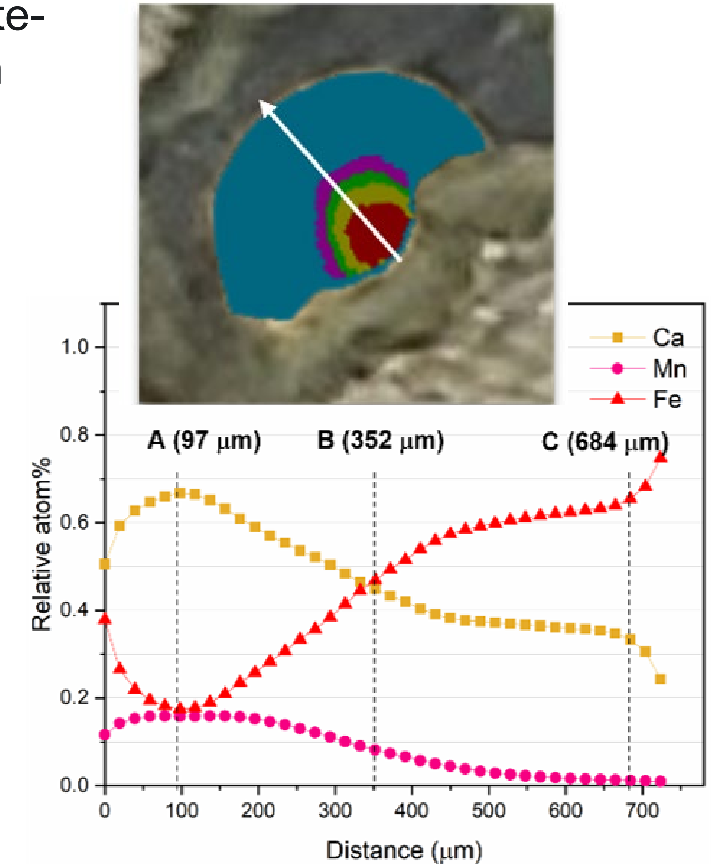
Depp et al., 2022, *ACS Earth & Space Chemistry*

Aragonite, ankerite, siderite, amorphous silica, and fibrous zeolite-like phase result from CO_2 injection (fate of Al and Si resolved)



Polites et al. 2022, *ES&T*

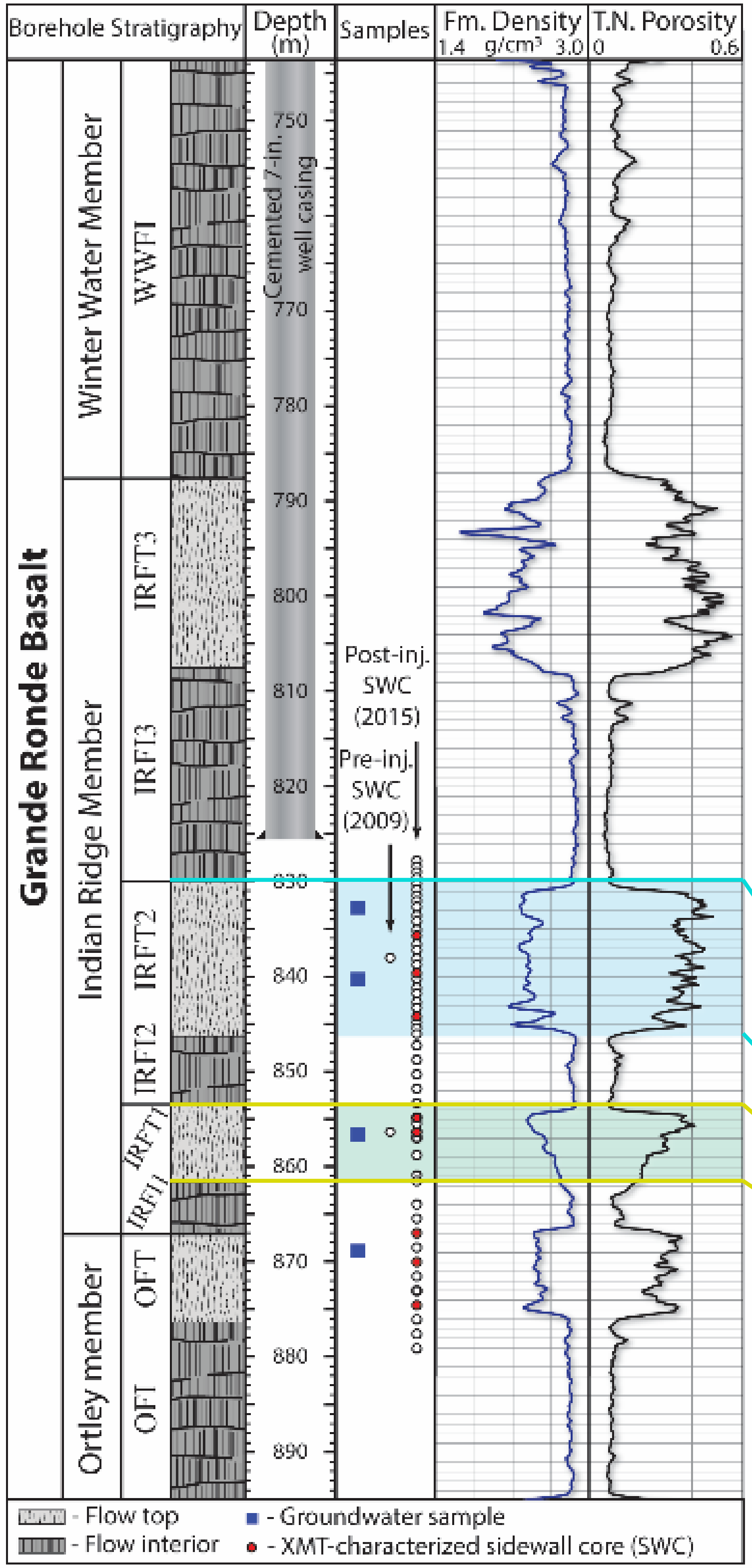
Complex chemical zonation of carbonate nodules:



Lahiri et al., 2023, *in review, ES&T*

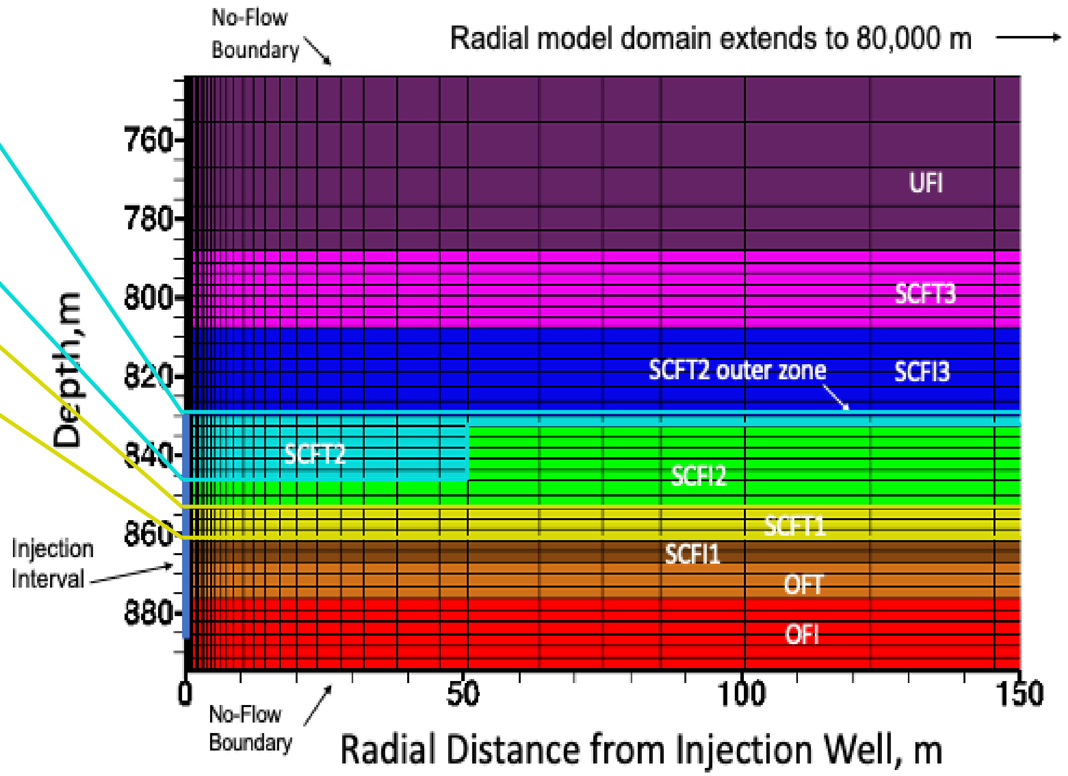
- Carbonate nodules were isotopically linked to injected CO_2
- XMT revealed carbonate nodules in the pore network – quantify the *specific surface area, porosity, permeability*
- SEM and EDS mapping revealed anthropogenic carbonate phases – Overall *carbon mineralization paragenesis*
- XRF and other analysis revealed composition zonation of Mn-rich center and Fe-rich rim - *reaction pathways* and *mechanisms*

Wallula Reactive Transport Simulation Setup



- STOMP-CO2 + ECKEChem with modified V8r6 thermodynamic database and our compiled kinetic parameters to describe the geochemistry
- Cylindrical coordinate system for depth of 743.7 – 894.6 m bgl, and a radial distance of 80 km from the well bore
- 977 tons of CO_2 was injected at the packed interval between 830 and 886 m below ground level into the two reservoirs and simulated for 10 years
- Previously reported and validated hydrogeologic properties of the modeled basalt storage system
- Basalt phases: plagioclase, clinopyroxene, glass, and magnetite
- TST-based Diss.-Ppt. model:

$$r = k_{ref} A\, exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\left(1-\frac{Q}{K_{eq}}\right)10^{(-\eta\, pH)}$$



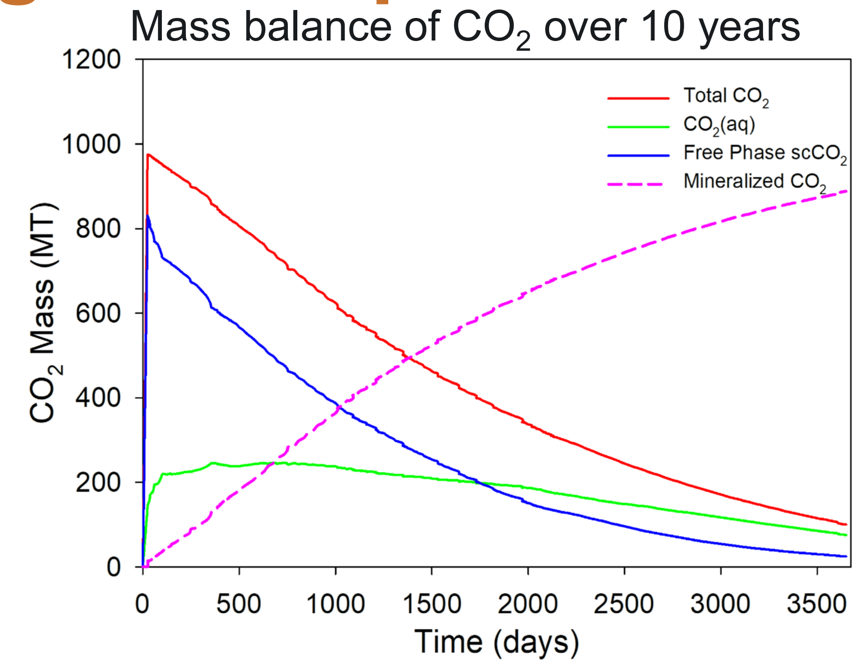
Outcomes of Reactive Transport Simulation:

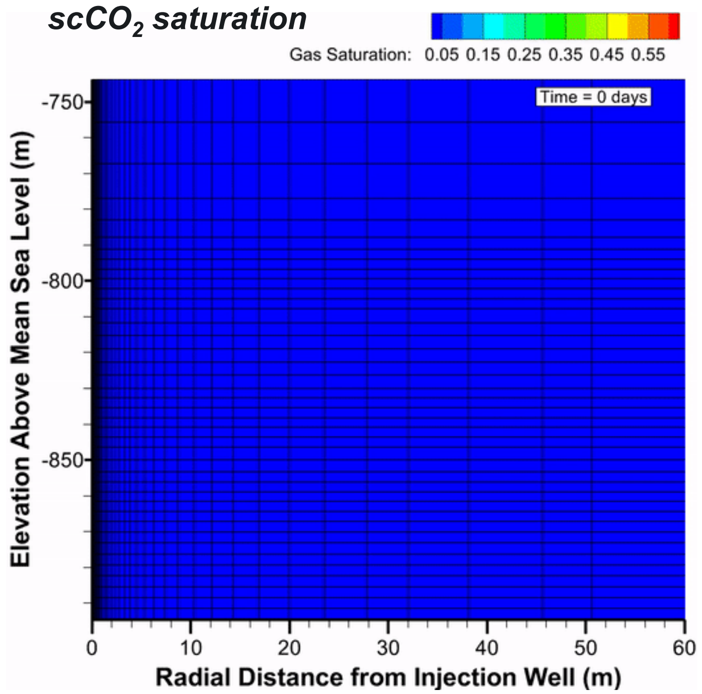
- Enable permitting
- Risk reduction
- Increase societal acceptance
- A Means for MRV (measurement, reporting, and verifying) for the sequestered CO_2 for tax credits
- Manage the reservoir and injection strategy to be efficient and sustainable

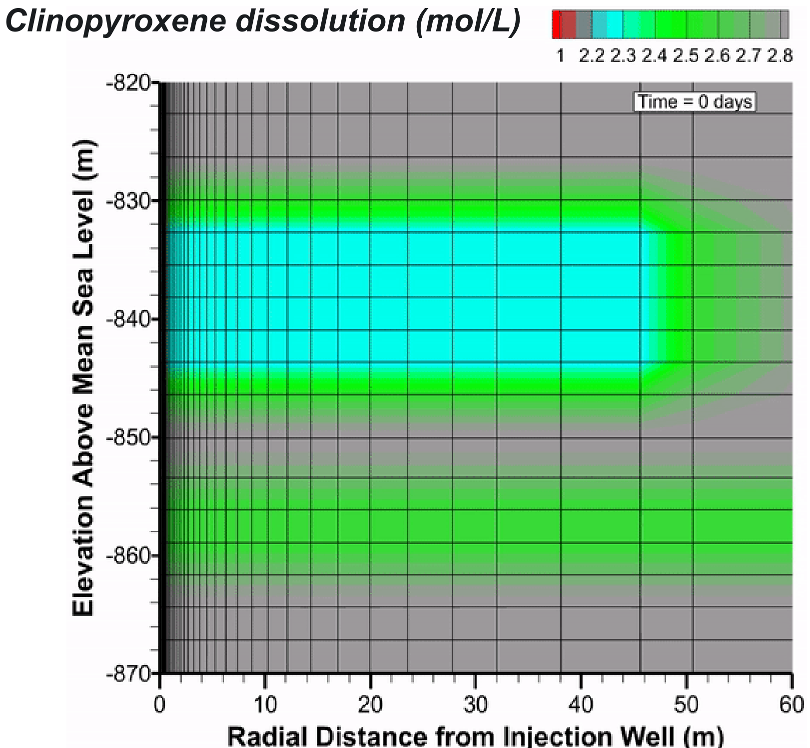
Quantifying and visualizing CO_2 transport, mineral dissolution, and precipitation guide injection strategies and reservoir management optimization

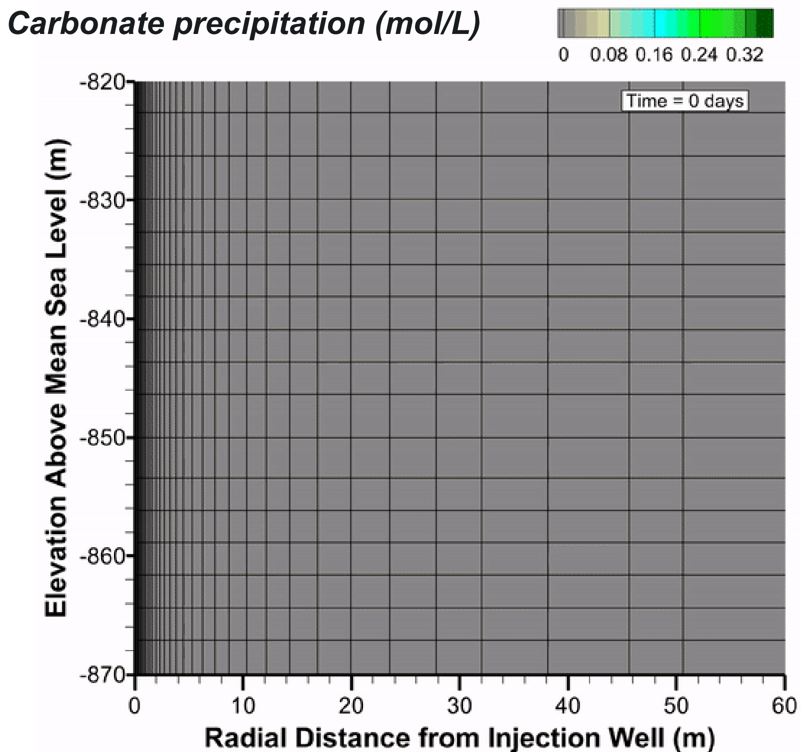
- After 10 years: ~3% in supercritical state, ~7% in aqueous phase, and ~90% of the injected CO_2 mineralized
- $scCO_2$ reaches maximum lateral extent of ~40 m away from the borehole after 30 months
- There were no measurable changes in porosity and permeability from wireline logs at Wallula
- Reactive transport simulation helps visualize the geochemistry-coupled drainage and imbibition processes that is critical to permitting and reservoir optimization

Cao et al., 2023, Reactive Transport Modeling of Anthropogenic Carbon Mineralization in Stacked Columbia River Basalt Reservoirs. In SPE/AAPG/SEG Unconventional Resources Technology Conference, p. D021S032R001. URTEC, 2023.









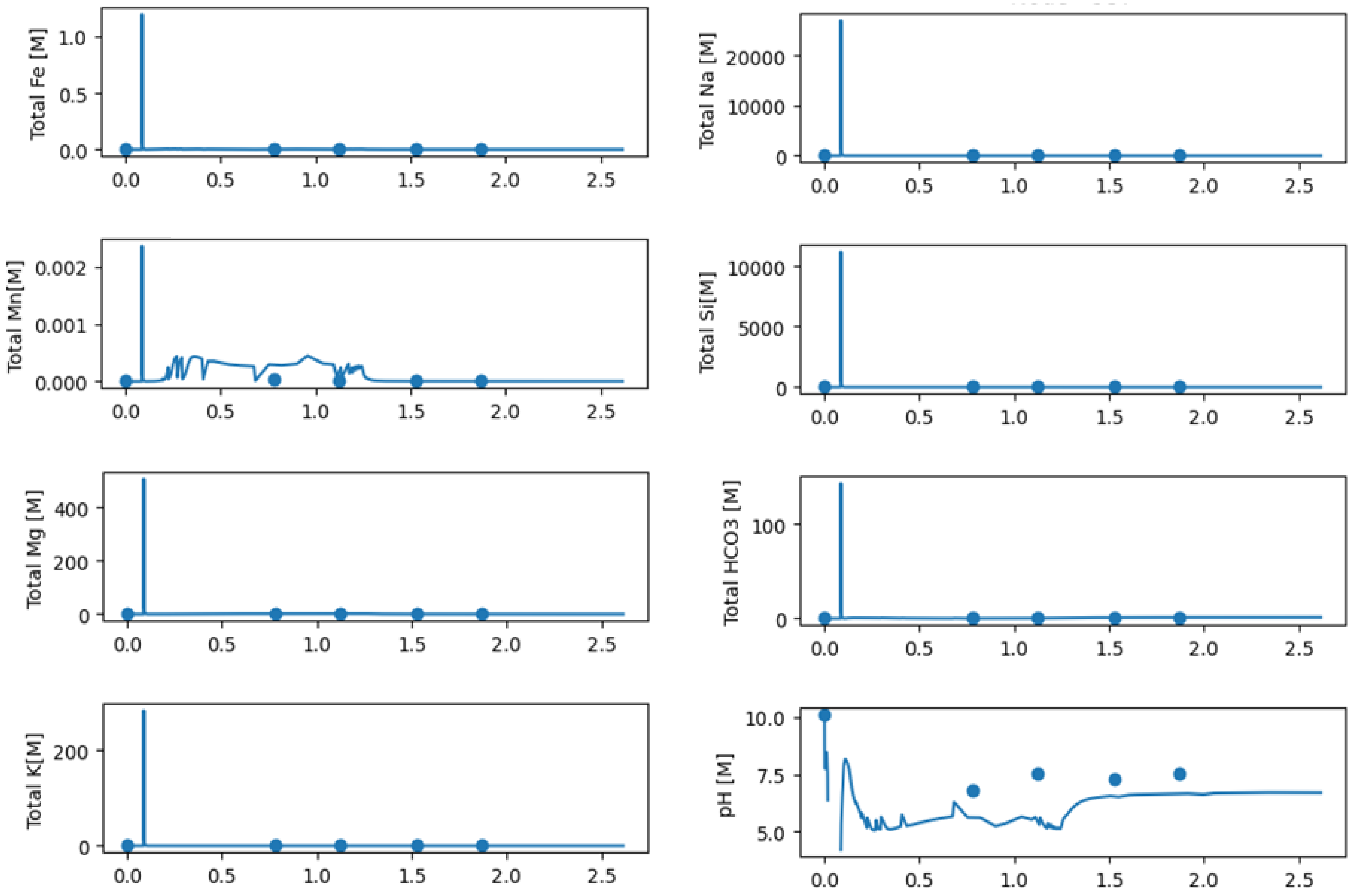
Simulated Aqueous Species Concentrations Aligned with Time-resolved Groundwater Chemistry

- Simulation results verified by time-resolved pre- and post-injection reservoir groundwater chemistry data

Opportunities:

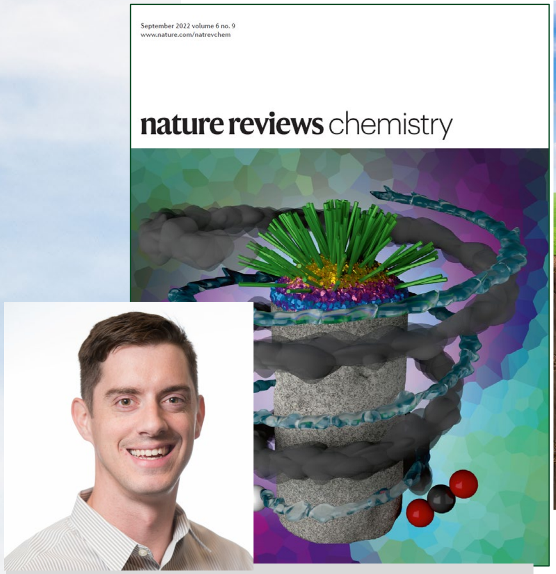
- Use verified reactive transport simulation as a monitoring tool for MRV

Injection Zone 1



DOE Office of Fossil Energy Carbon Management (FECM)
Darin Damiani (DOE HQ)
Carbon Utilization and Storage Partnership (CUSP)

U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management



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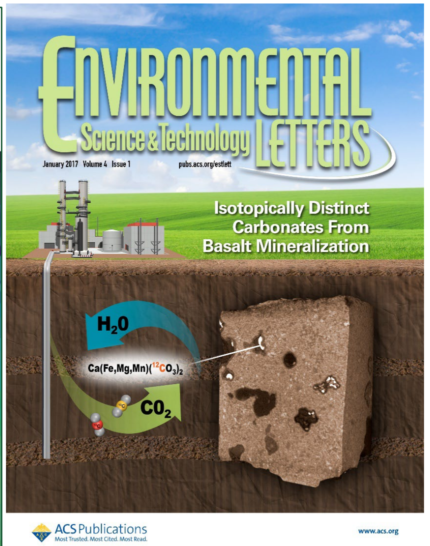
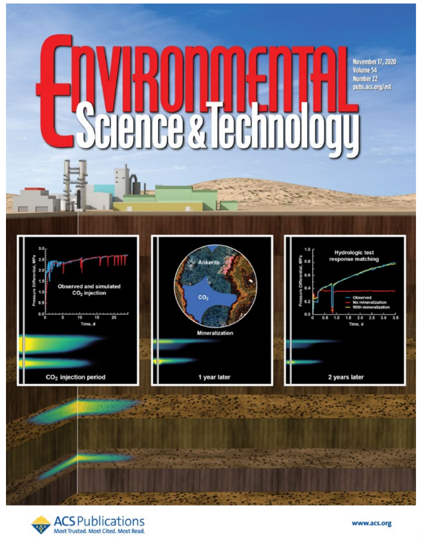
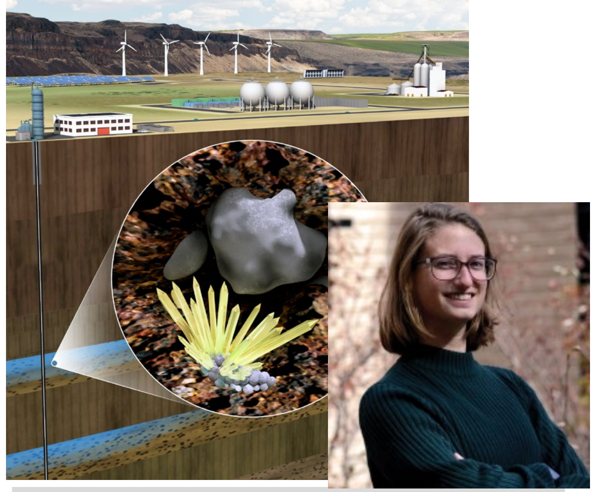




Depp et al., 2022, Pore-scale Microenvironments Control Anthropogenic Carbon Mineralization Outcomes in Basalt, ACS Earth & Space Chemistry



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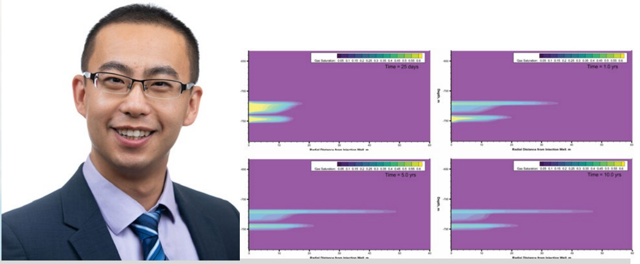

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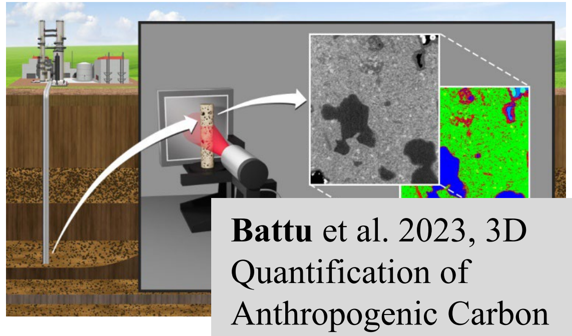
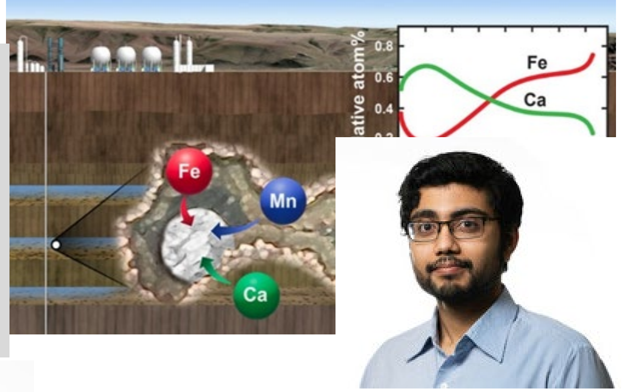
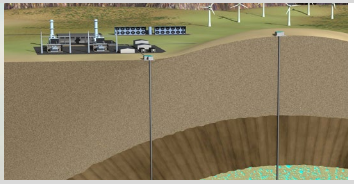


Battu et al. 2023, 3D Quantification of Anthropogenic Carbon Mineralization and Pore Networks in Stacked Basalt Reservoirs, submitted





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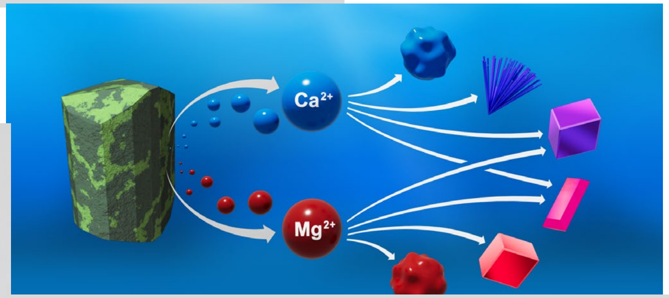

Aguila et al. 2023, Kinetics of Diopside Reactivity for Carbon Mineralization in Mafic-Ultramafic Rocks, under review.

Lahiri et al. 2023, Facile Metal Release from Pore-lining Phases Enables Unique Carbonate Zonation in a Basalt Carbon Mineralization Demonstration, under review.